Results from the MINOS Experiment

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On behalf of the MINOS Collaboration

FNAL Users' Meeting
2009-6-3

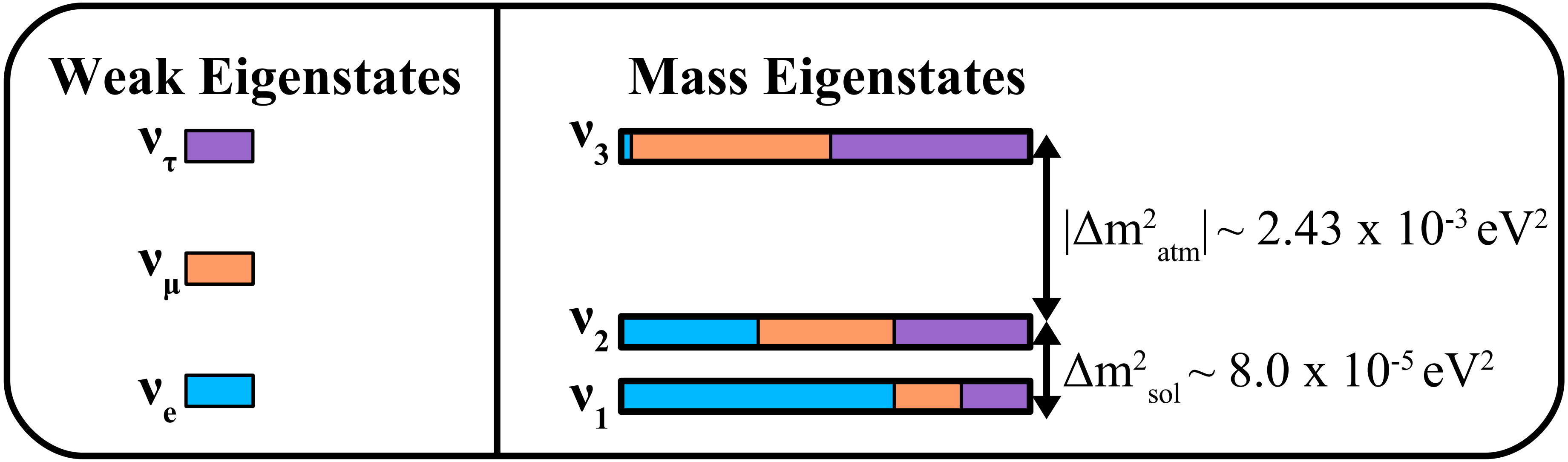
MINOS Collaboration

140 Physicists from 28 institutions

Argonne • Athens • Benedictine • Brookhaven • Caltech • Cambridge • Campinas • Fermilab • Harvard • Holy Cross • IIT • Indiana • Minnesota-Twin Cities • Minnesota-Duluth • Otterbein • Oxford • Pittsburgh • Rutherford • Sao Paulo • South Carolina • Stanford • Sussex • Texas A&M • Texas-Austin • Tufts • UCL • Warsaw • William & Mary

Main Injector Neutrino Oscillation Search

The primary function of the MINOS experiment is to study neutrino oscillations at the atmospheric mass-squared splitting



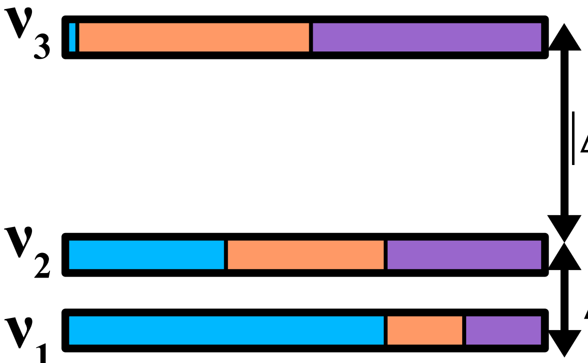
Mass eigenstates are a linear combination of weak states

Oscillations at the Atmospheric Splitting

A ν of one flavor will become a superposition of other flavors as it propagates

$$P(\nu_\alpha \to \nu_\beta) = \delta_{\alpha\beta} - 4\sum_{i>j} \mathcal{R}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2[1.27 \Delta m^2_{ij}(L/E)] + 2\sum_{i>j} \mathcal{I}(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin[2.54 \Delta m^2_{ij}(L/E)]$$

Mass Eigenstates



- $\Delta m^2_{atm} >> \Delta m^2_{sol}$
- For $E/L \sim \Delta m^2_{atm}$ terms with that mass term dominate the probability
- MINOS L/E is tuned to this scale

For one mass scale dominance

$$P(\nu_\alpha \to \nu_\beta) \approx S_{\alpha\beta} \sin^2[1.27 \Delta m^2 (L/E)], \quad \text{for } \alpha \neq \beta$$

$S_{\alpha\beta}$ term is related to components of the mixing matrix

Oscillations Studied at MINOS

The following analyses will be covered in this presentation

Oscillations Studied at MINOS

The following analyses will be covered in this presentation

- $\nu_\mu \rightarrow \nu_\tau$ oscillations
  - Study oscillations through the disappearance of ν_μ CC events
  - Identify ν flavor by finding muons from CC interactions
  - Measure:
    - $|\Delta m^2_{32}|$
    - $\sin^2(2\theta_{23})$
  - Rule out exotic models:
    - Decoherence
    - Decay

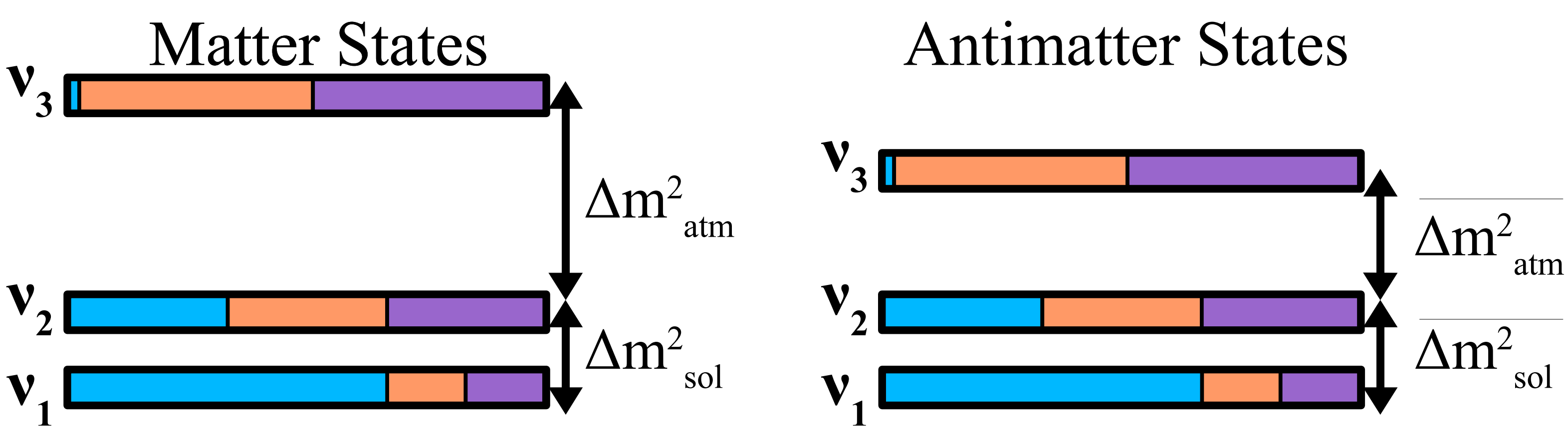
Neutrino Survival Probability

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2 L/E)$$

Oscillations Studied at MINOS

The following analyses will be covered in this presentation

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_\tau$ oscillations
  - Study oscillations through the disappearance of $\bar{\nu}_\mu$ CC events
  - Identify ν flavor by finding antimuons from CC interactions
  - Measure:
    - $|\overline{\Delta m^2_{32}}|$
    - $\sin^2(2\overline{\theta_{23}})$
  - Test of CPT conservation and/or nonstandard interactions

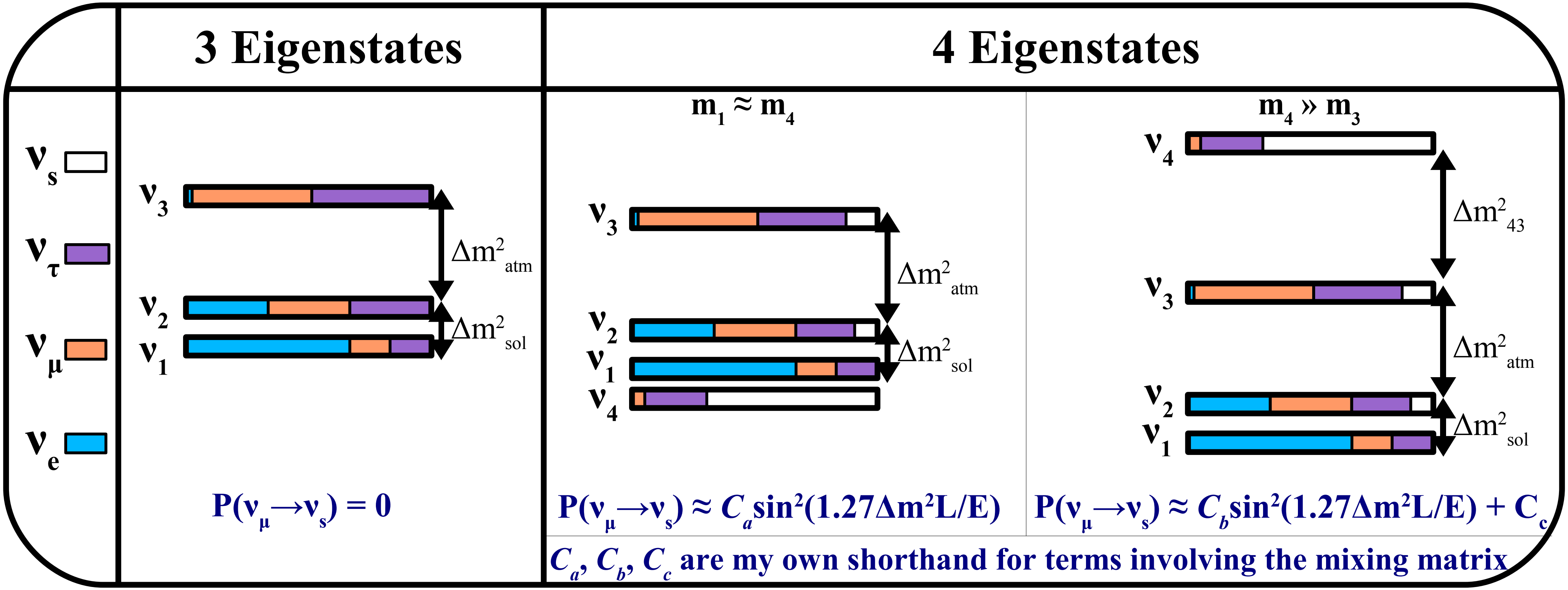


$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu) \approx 1 - \sin^2(2\overline{\theta}_{23})\sin^2(1.27\overline{\Delta m^2}L/E)$$

Oscillations Studied at MINOS

The following analyses will be covered in this presentation

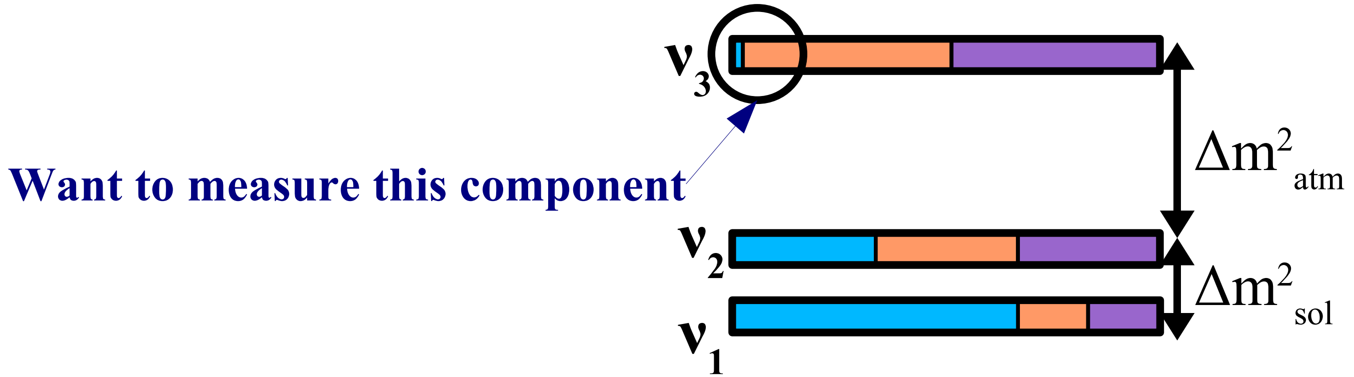
- Sterile neutrinos: $\nu_\mu \to \nu_s$ oscillations
  - Identify active ν by identifying NC interactions
  - Study oscillations through the disappearance of NC events
  - Sensitive to:
    - f_s, θ_{24}, θ_{34}



Oscillations Studied at MINOS

The following analyses will be covered in this presentation

- $\nu_\mu \rightarrow \nu_e$ oscillations
  - Study oscillations through the appearance of ν_e CC events
  - Identify ν flavor by finding electrons from CC interactions
  - Sensitive to:
    - $\sin^2(2\theta_{13})$
    - δ_{CP}
  - θ_{13} is the only unmeasured mixing angle in 3 flavored lepton sector
  - CP violating effects involve θ_{13} terms



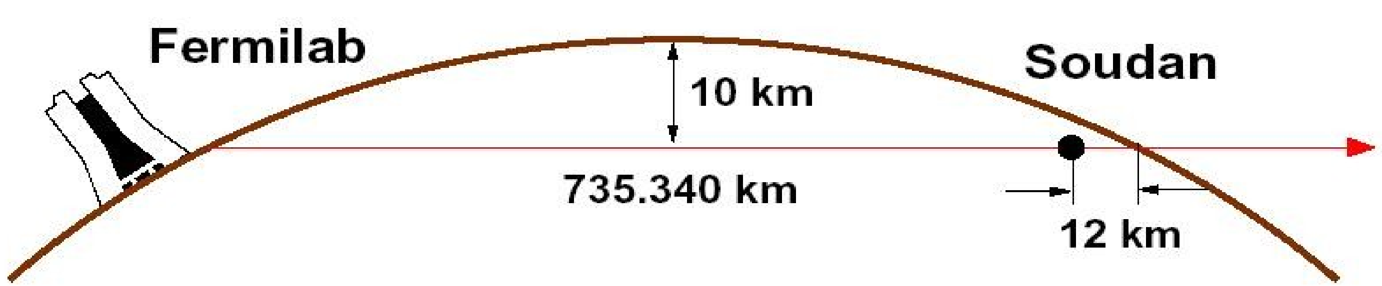
$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2 L/E)$+"$\delta_{CP}$-terms"+"mass hierarchy sensitive terms"+...

All these terms are significant. Matters effects will alter the probability

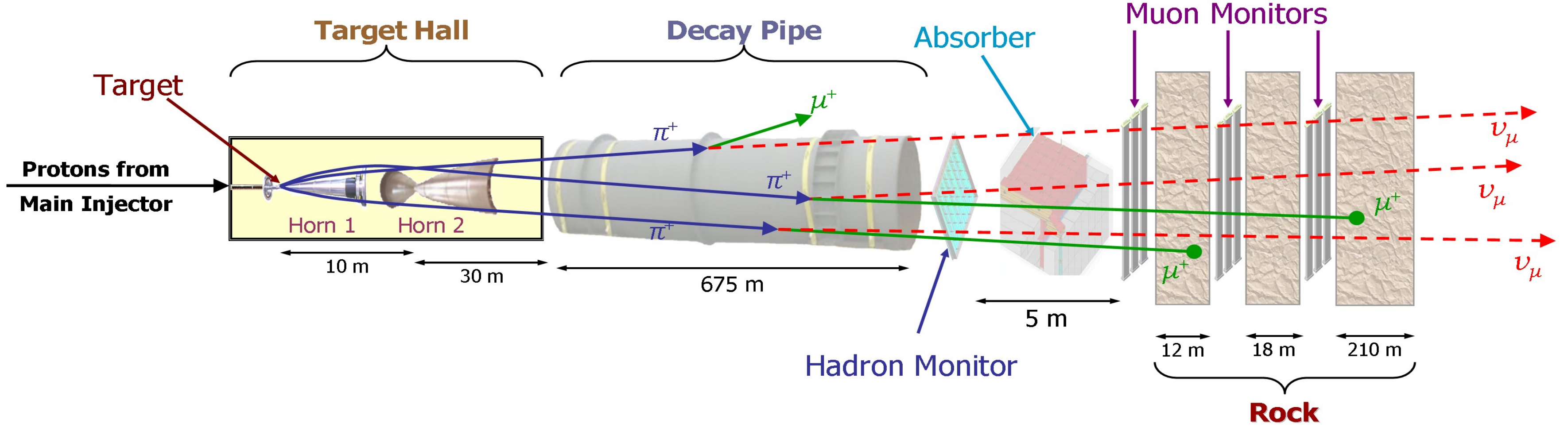
How do we study these oscillations?

Long Baseline Accelerator Neutrinos

- Use a neutrino beam derived from 120 GeV protons from Fermilab's Main Injector
- Use 2 functionally identical detectors:
  - A Near Detector at Fermilab to measure the unoscillated beam composition and the energy spectrum
  - A Far Detector deep underground in the Soudan Mine in Minnesota to search for evidence of oscillations
  - Extrapolate Near Spectrum to the Far Detector to minimize uncertainties due to:
    - Cross section, flux, event detection and selection

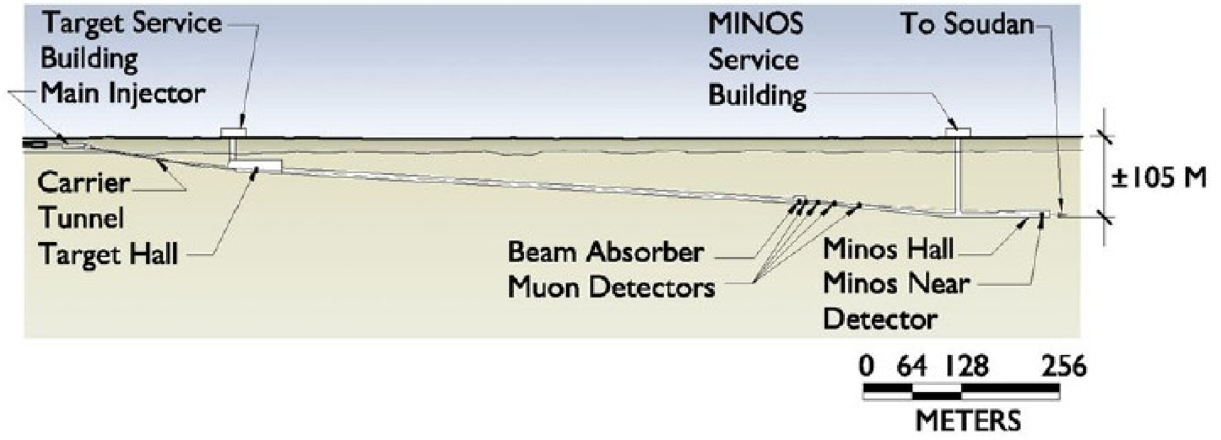


NuMI (Neutrinos at the Main Injector) Beam



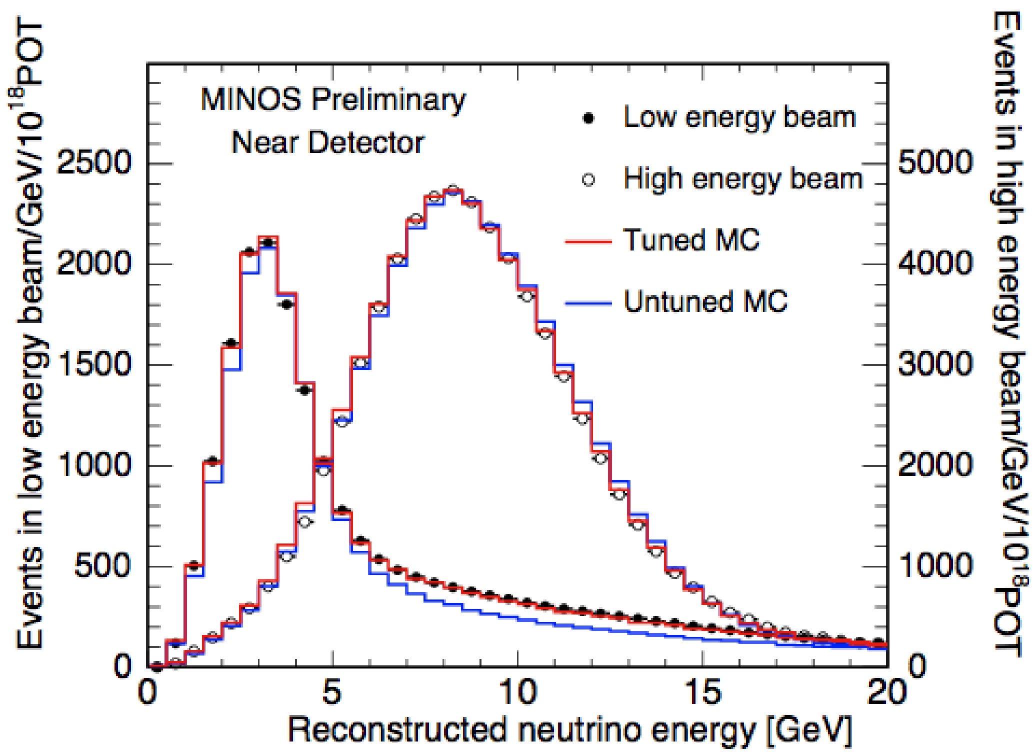
Protons are guided towards a graphite target producing a stream of mesons

2 magnetic horns are optimized to focus positively charged particles whose subsequent decays produce neutrinos



NuMI Beam Composition

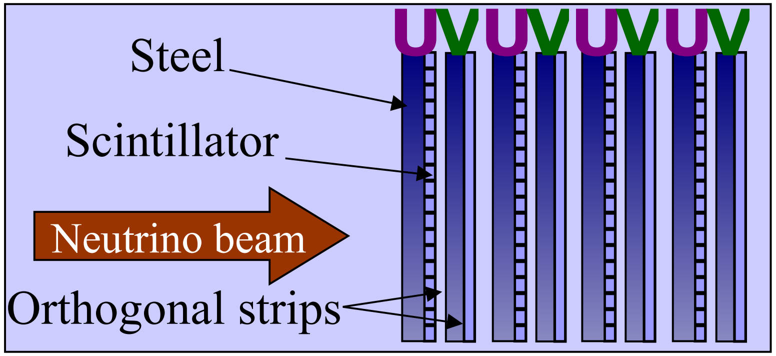
- The resulting neutrino energy spectrum can be modified by adjusting the relative position of the target and the horns
- The default configuration is "Low Energy" which optimizes our L/E for the atmospheric mass-squared splitting

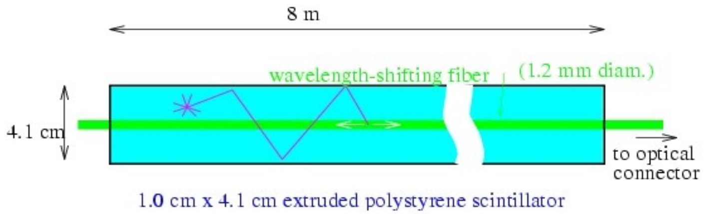


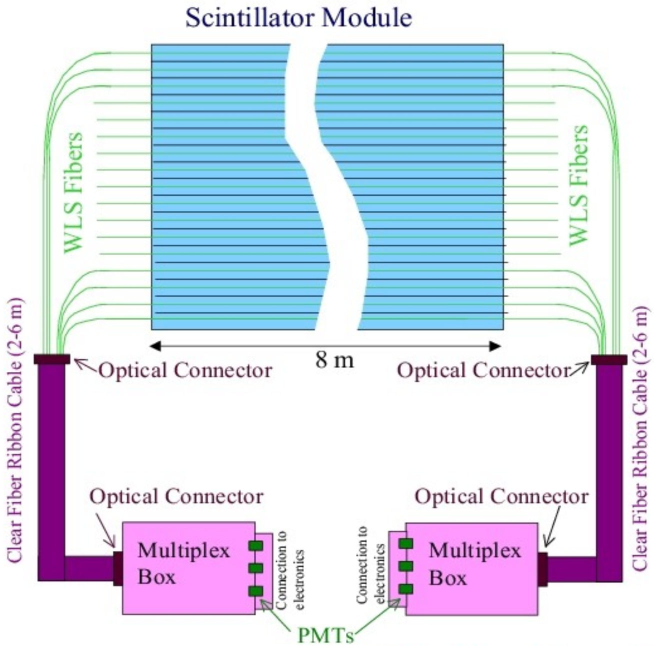
- CC interactions in the Near Detector are:
  - 92% ν_μ
  - 7% $\overline{\nu}_\mu$
  - 1% $\nu_e + \overline{\nu}_e$

2 Detector Experiment

- Functionally identical tracking calorimeters with alternating layers of steel and scintillator
  - 2.54cm thick magnetized steel planes:
    - <B> = 1.2 T
    - Muon Charge & Momentum Measurements
  - 1cm thick scintillator planes
    - Segmented into 4.1cm wide strips
    - Alternating planes rotated by 90^{o}
      - Reconstruct 3D position
  - Sample Frequency: 1.4 radiation lengths
  - 1 GeV/c muon travels ~20 planes
  - Light transported through wavelength shifting and clear fibers
  - Signal read out through mutil-anode Hamamatsu PMTs
- Some differences due to flux considerations
  - Number of interactions per beam spill
  - Detector Size: 1kton (Near) vs 5.4kton (Far)
  - M64 (Near) vs M16 (Far) PMT
  - Multiplexing (Far)
  - Single Ended readout in Near



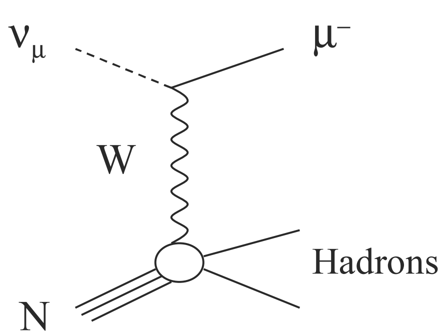


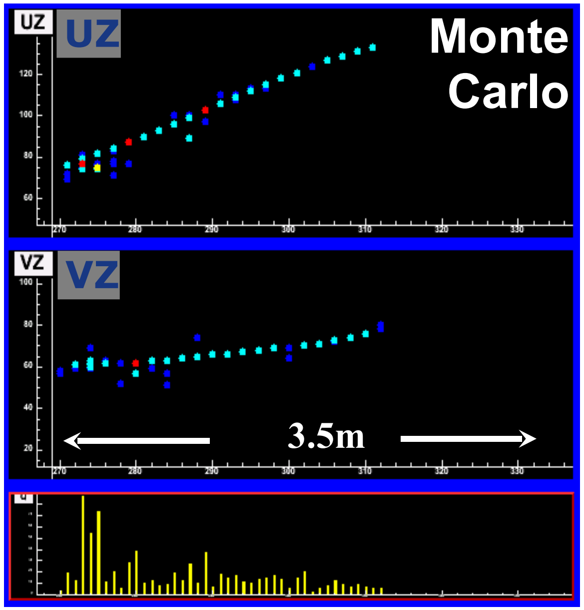


Objects not to scale

Event Topologies

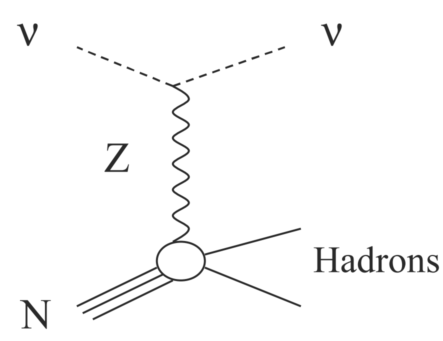
ν_μ CC Event

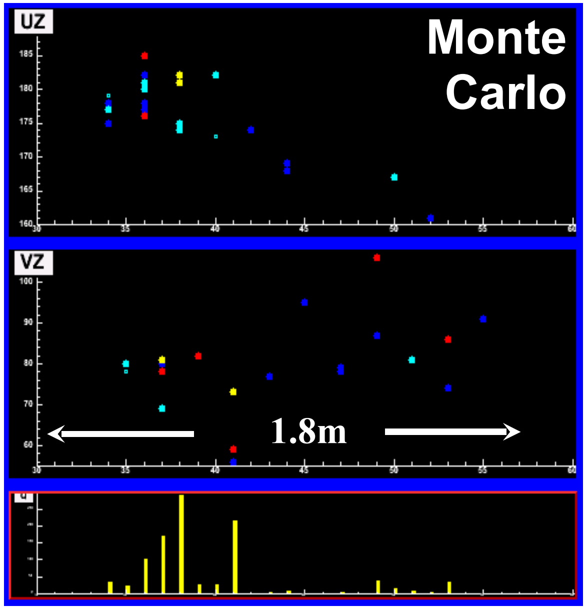




Long muon track & hadronic activity at vertex

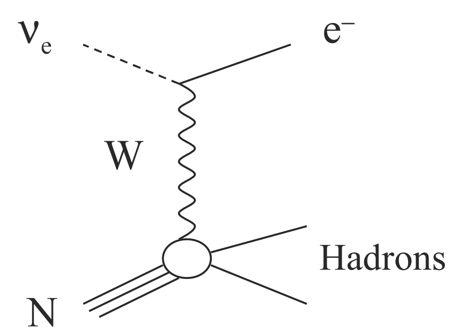
NC Event

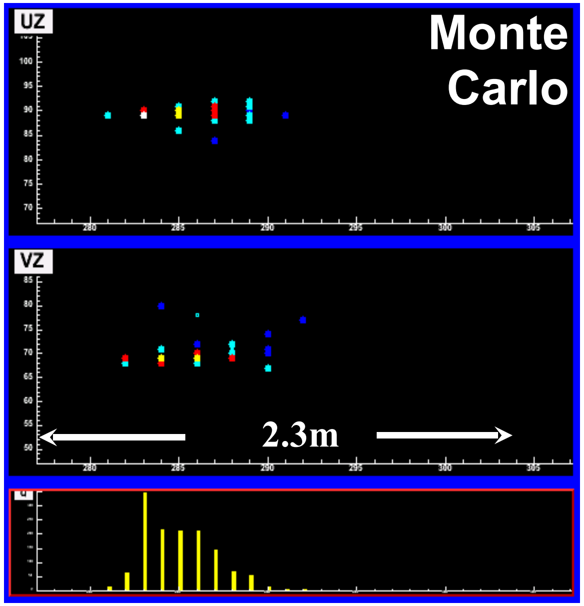




Short event
Often diffuse

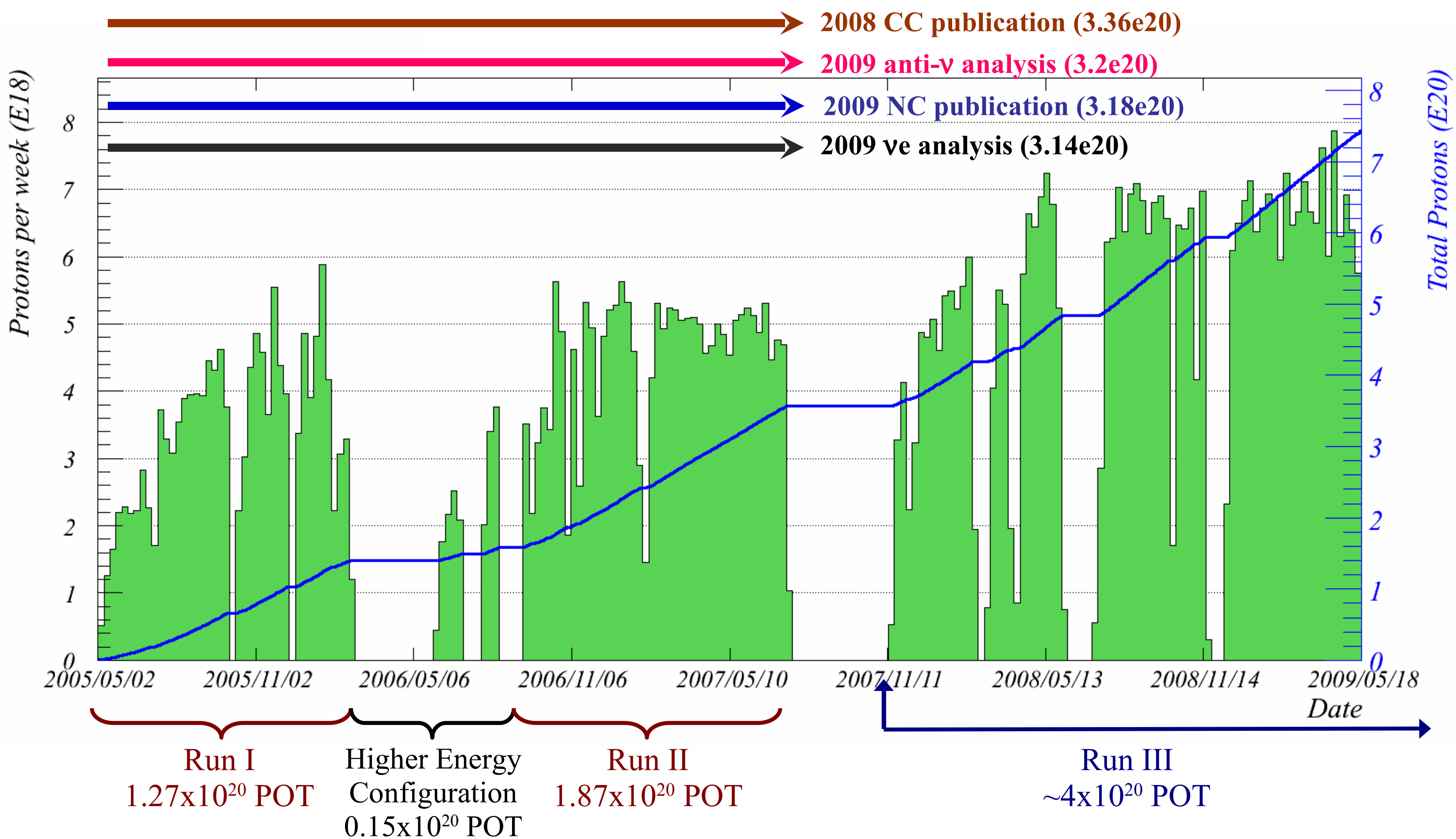
ν_e CC Event





Compact event
EM shower profile

Total Protons on NuMI Target



ν_μ Charged Current Disappearance

with 3.36×10^{20} POT

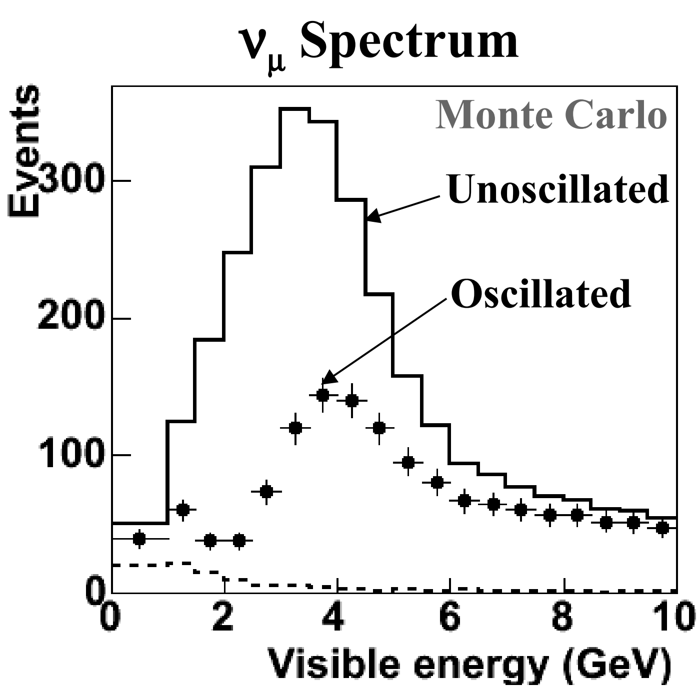
Measurements of $\sin^2(2\theta_{23})$, $|\Delta m^2_{32}|$

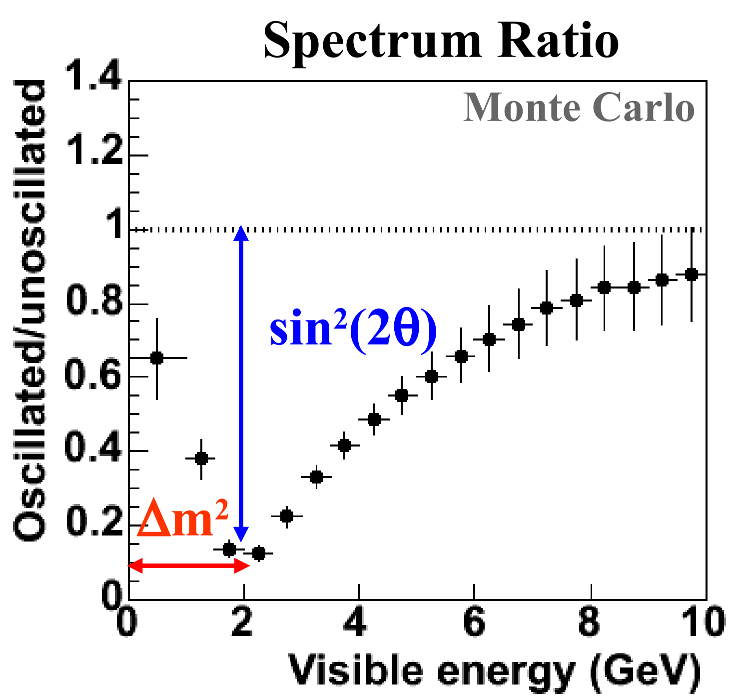
Published: Phys. Rev. Lett. **101** 131802 (2008)

ν_μ CC Disappearance – The Purpose

- Looking for a deficit of ν_μ events in the Far Detector
  - Precision measurements of atmospheric Δm^2 and $\sin^2(2\theta)$
  - Test the neutrino oscillation hypothesis

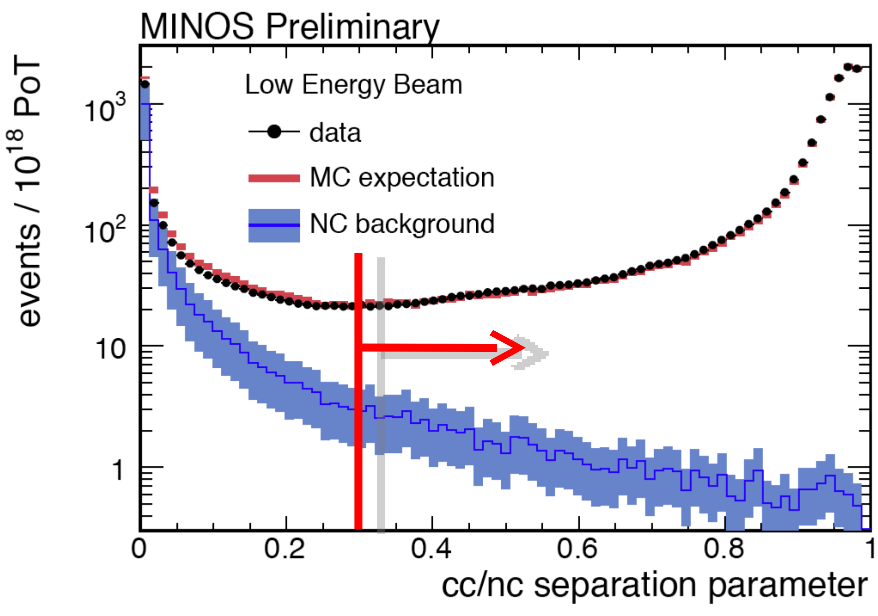
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27 \Delta m^2 L}{E}\right) \quad , \quad L=735\text{ km}$$

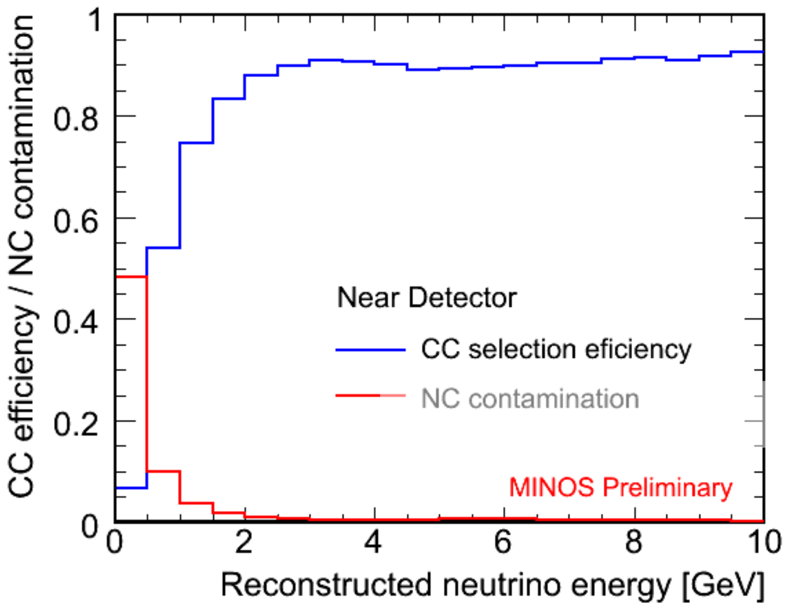




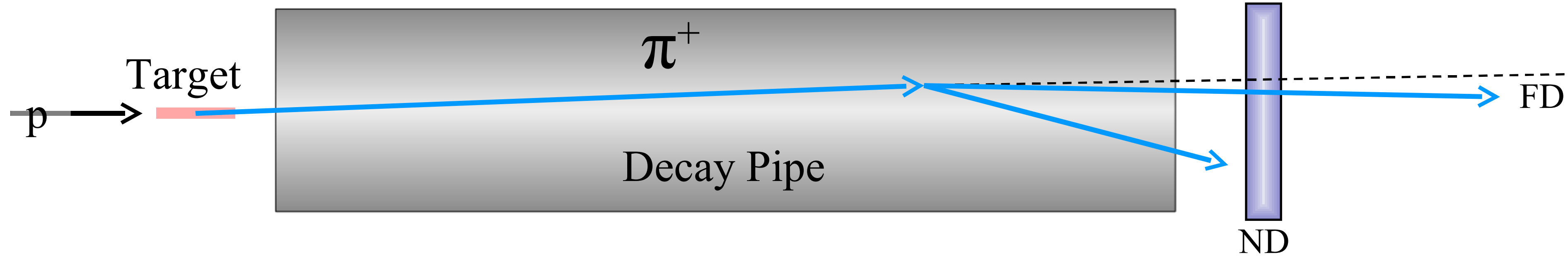
ν_μ CC Disappearance – The Selection

- ν_μ CC-like events are selected with a nearest neighbors (kNN) based algorithm with four inputs based on hits belonging to the track:
  - Track length (planes)
  - Mean pulse height/plane
  - Fluctuation in pulse height
  - Transverse track profile

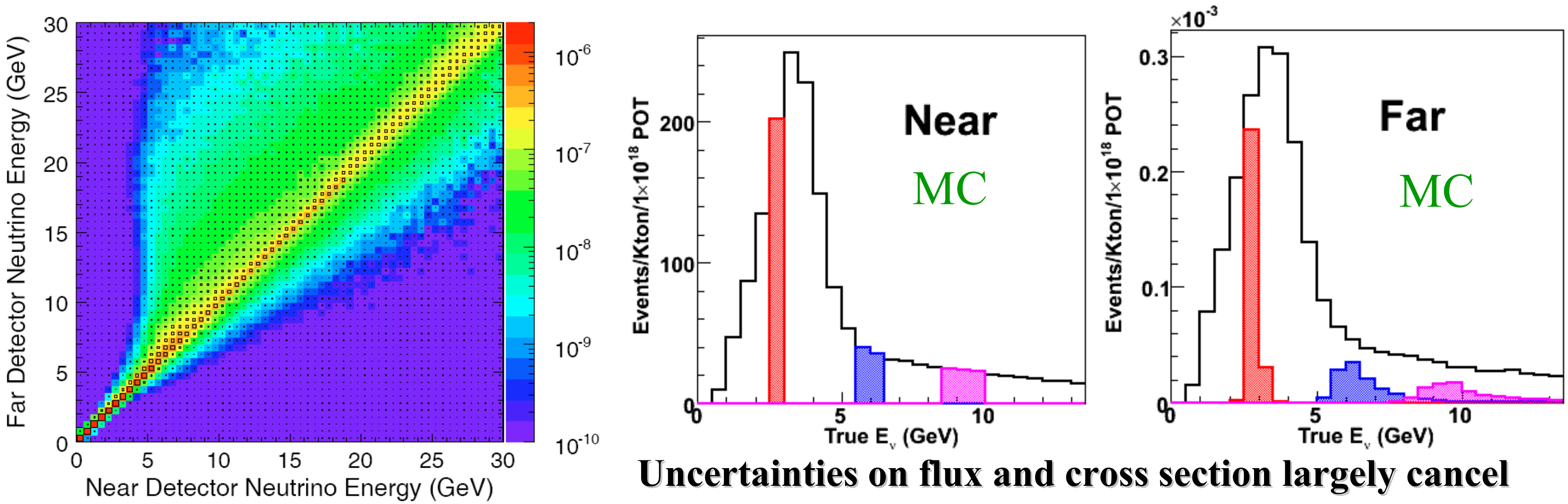




ν_μ CC Disappearance – Near to Far Extrapolation



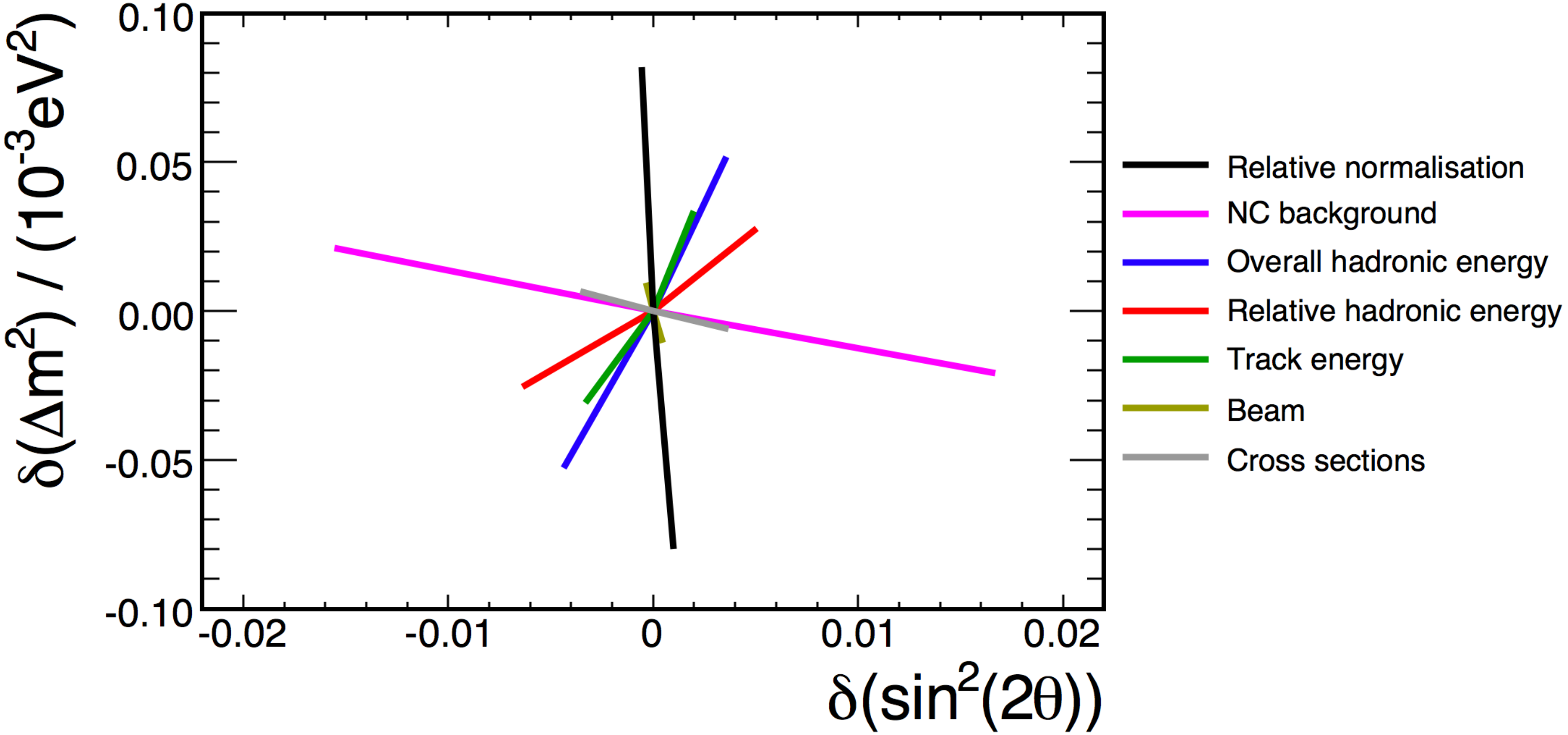
- The observed Near spectrum is extrapolated to the Far Detector
  - Use Monte Carlo to provide corrections due to energy smearing and acceptance
  - Encode pion decay kinematics & angular acceptance into a matrix used to transform the ND spectrum into the FD energy spectrum



Uncertainties on flux and cross section largely cancel

ν_μ CC Disappearance – Systematic Uncertainties

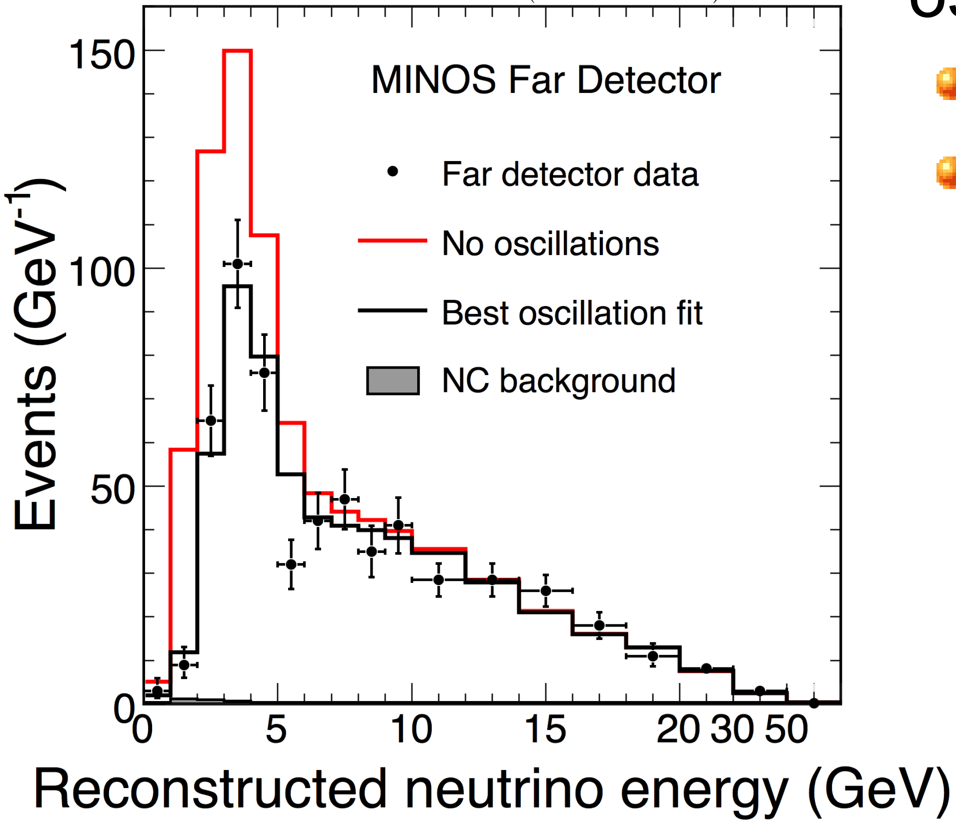
- The impact of different sources of systematic uncertainty are evaluated by fitting modified MC in place of the data



- The 3 largest sources of uncertainty are included as nuisance parameters in the oscillation fit
  - Far/Near Normalization (4%)
  - Absolute Hadronic Energy Scale (10.3%)
  - NC Contamination (50%)

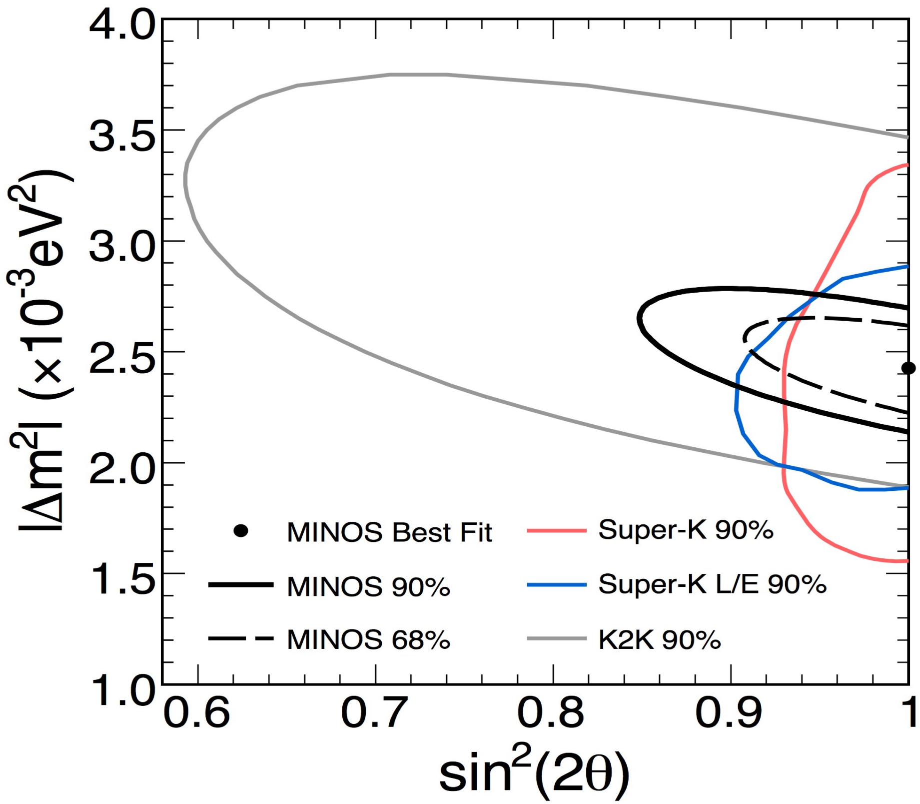
ν_μ CC Disappearance – Oscillation Results

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(\frac{1.27\Delta m^2 L}{E}\right)$$



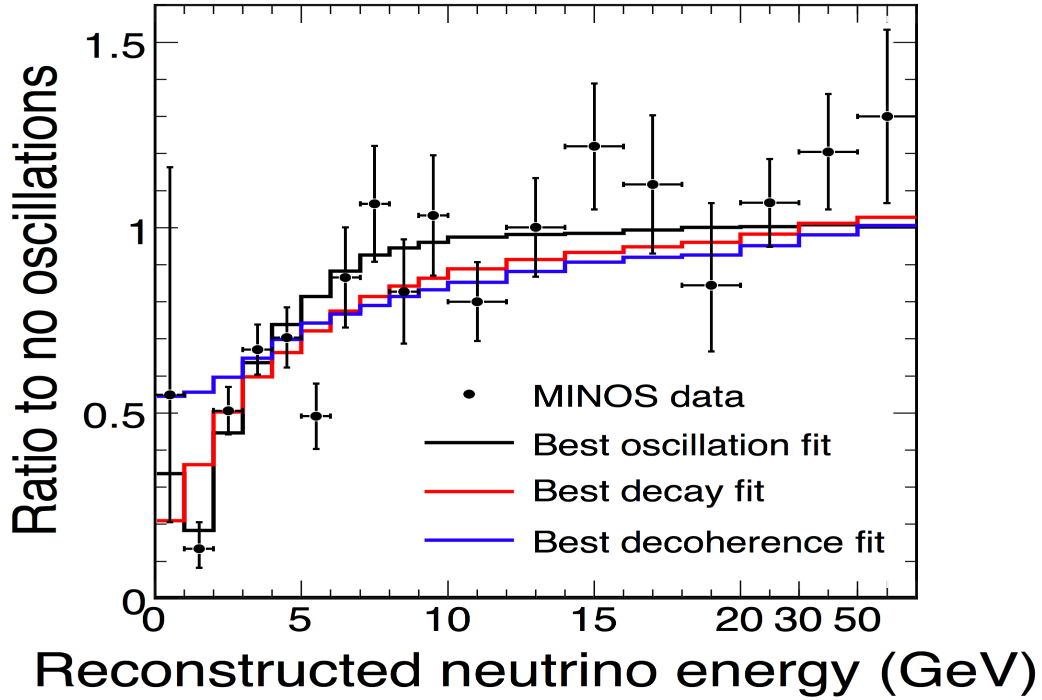
- Far Data consistent with two-flavor oscillations with χ^2/NDF = 90/97
  - **$|\Delta m^2_{32}| = 2.43 \pm 0.13 \times 10^{-3}\,\mathrm{eV}^2$ (68% C.L.)**
  - **$\sin^2(2\theta_{23}) > 0.90$ (90% C.L.)**

  Note results are constrained to physical region $\sin^2(2\theta_{23}) < 1$



- The resulting contour includes the 3 largest systematic uncertainties

ν_μ CC Disappearance – Alternative Models



- Decay Model
  - $P_{\mu\mu} = [\sin^2\theta + \cos^2\theta \exp(-\alpha L/2E)]^2$

    V. Barger *et al.*, PRL82:2640(1999)
  - χ^2/ndof = 104/97
  - $\Delta\chi^2$ = 14 w.r.t. oscillation model
  - disfavored at 3.7σ
- Decoherence Model
  - $P_{\mu\mu} = 1 - \frac{\sin^2 2\theta}{2}\left(1 - \exp\left(\frac{-\mu^2 L}{2E}\right)\right)$

    G.L. Fogli *et al.*, PRD67:093006 (2003)
  - χ^2/ndof = 123/97
  - $\Delta\chi^2$ = 33 w.r.t. oscillation model
  - disfavored at 5.7σ

$\bar{\nu}_\mu$ Charged Current Disappearance

with 3.2 x 10^{20} POT

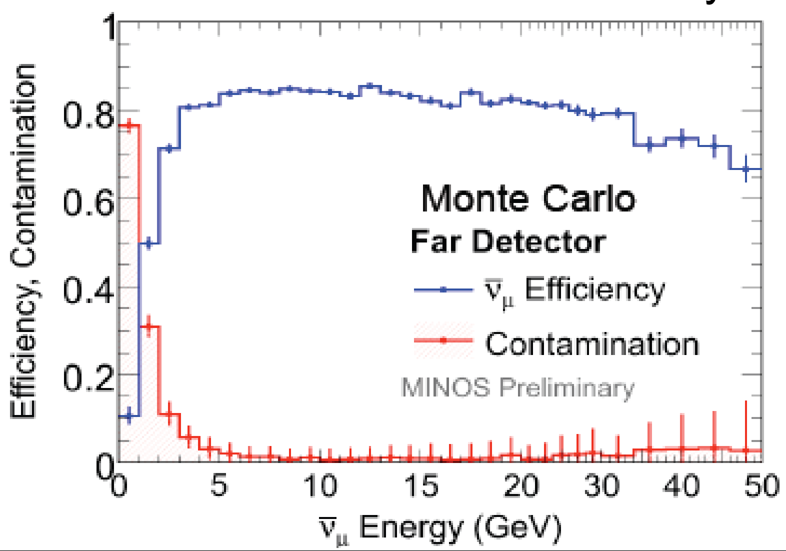
Measurements of $\sin^2(2\bar{\theta}_{23})$, $|\overline{\Delta m^2_{32}}|$

To be submitted

Presented at FNAL Wine & Cheese 4 weeks ago

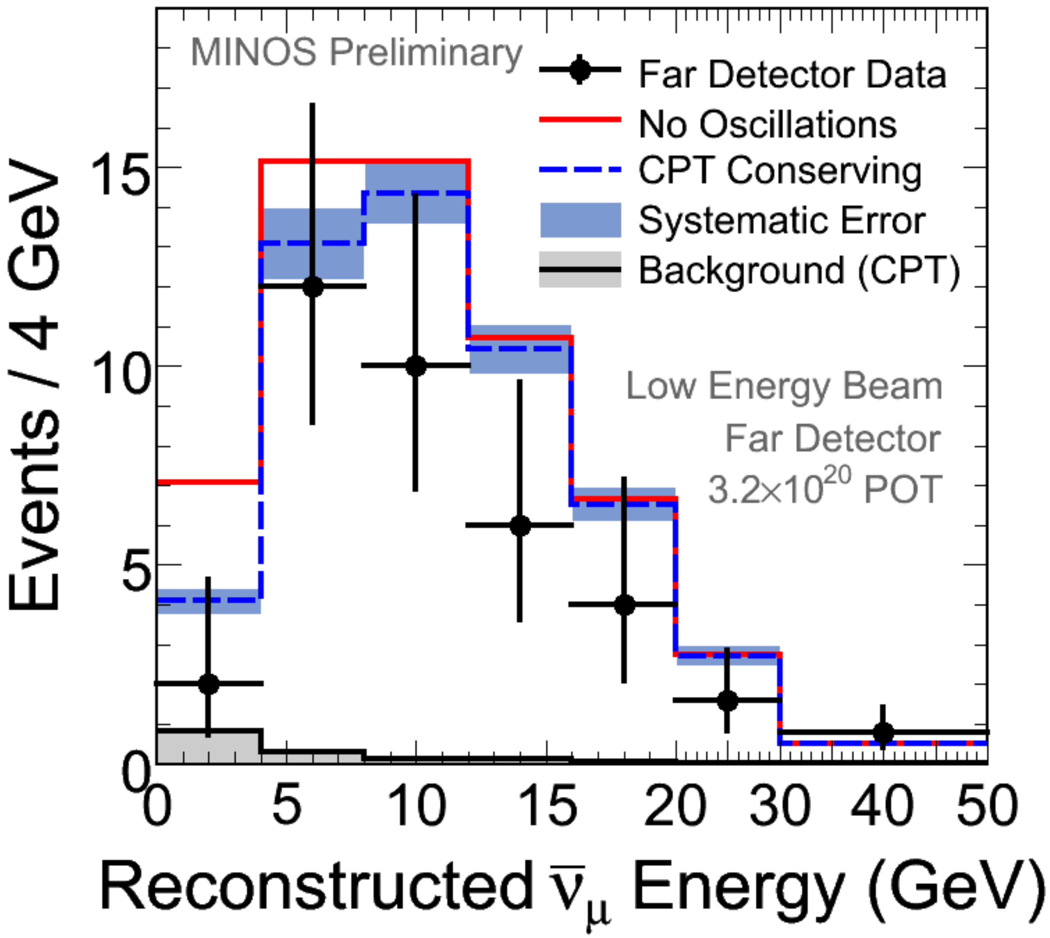
$\overline{\nu}_\mu$ CC Disappearance – The Purpose & Selection

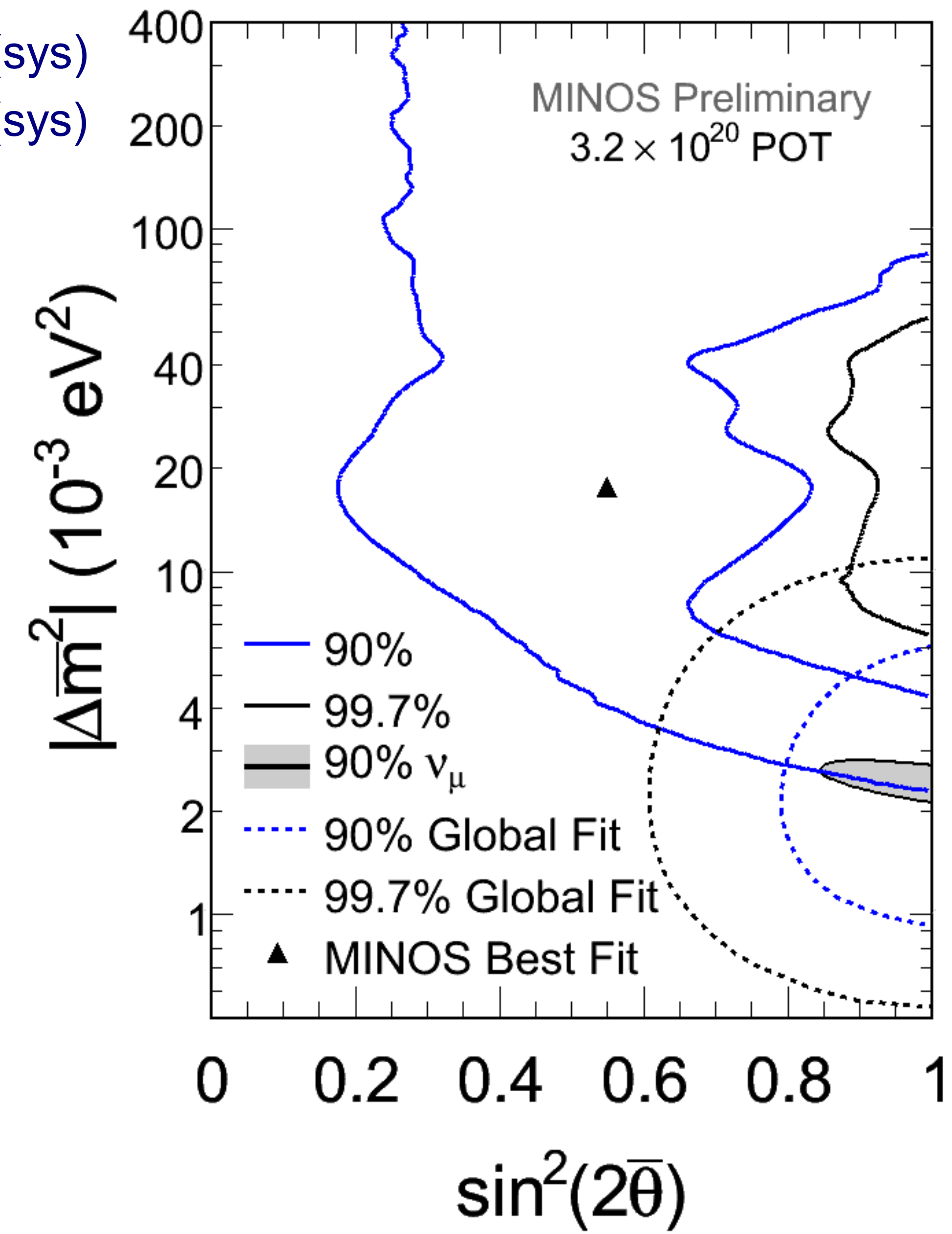
- Looking for a deficit of $\overline{\nu}_\mu$ events in the Far Detector
  - Test if antineutrino oscillations are identical to neutrino oscillations
- Similar to previous ν_μ analysis but we select positively charged tracks
- There are differences though
  - Flux is different (*ie* production in the decay pipe walls is significant)
  - $\overline{\nu}_\mu$ CC events are only 7% of the beam
  - Hence charge misidentified muon and NC backgrounds are relatively larger
  - Developed extra cuts:
    - Likelihood based on track length, pulse height in track, pulse height in plane
    - Charge sign significance of the track fit
    - Relative angle: Does the track bend towards or away from the coil?



$\overline{\nu}_\mu$ CC Disappearance – Oscillation Results

Far Prediction (no oscillations): 64.6 ±8(stat) ±3.9(sys)
Far Prediction (CPT conserving): 58.3 ±7.6(stat)±3.6(sys)
Far Data: 42 events
1.9σ less than CPT conserving oscillations





Neutral Current Disappearance

with 3.18 x 10^{20} POT

Search for sterile neutrinos

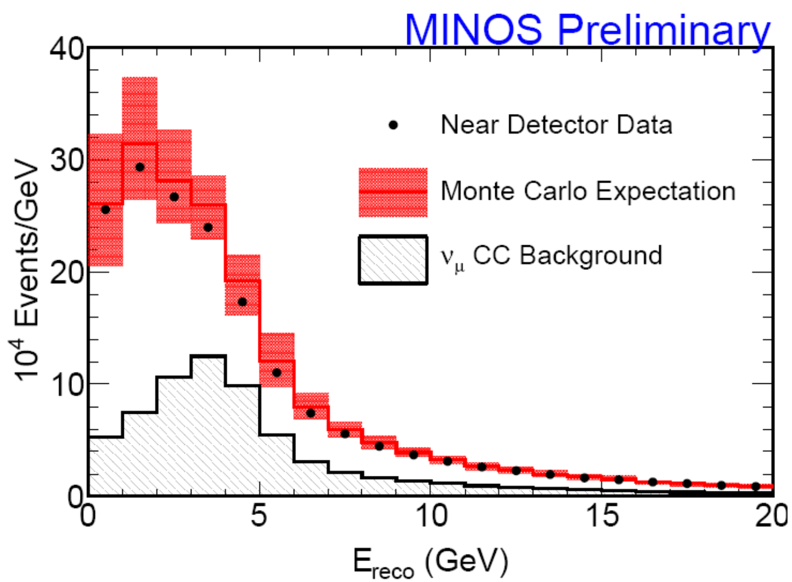
Update to PRL [Phys. Rev. Lett. **101** 221804 (2008)]

To be submitted to PRD

Christopher Backhouse will cover this analysis during Session 7 tomorrow afternoon

NC Analysis – Near Spectrum

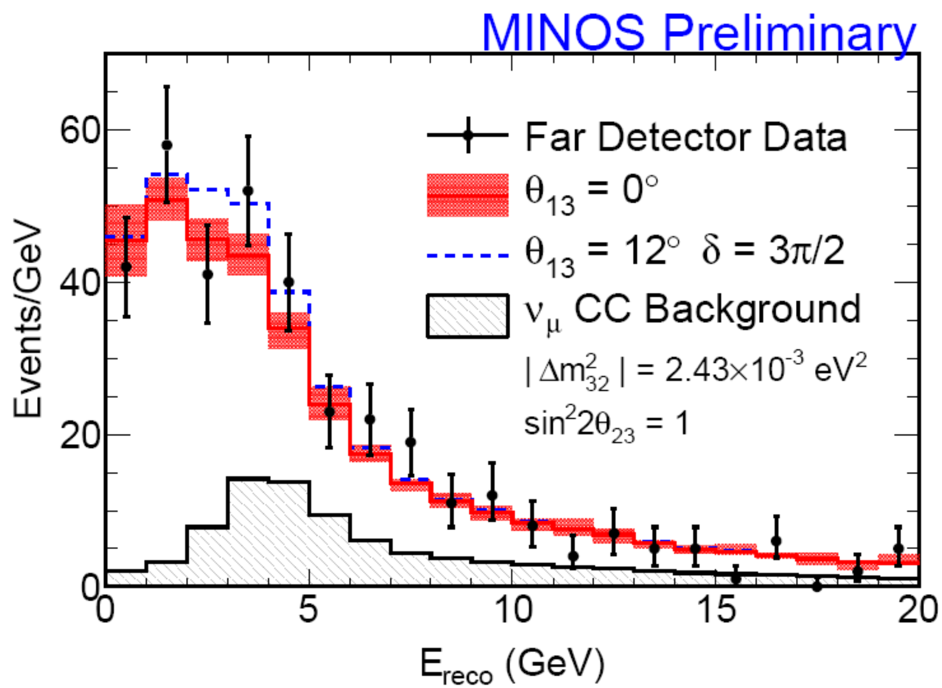
- Identify NC interactions by selecting showers with no muons
  - See Backhouse's talk for more details



- Extrapolate the selected Near spectrum to the Far in bins of visible energy
- Far Detector prediction depends on oscillation parameters
  - CC parameters set to values measured by the CC analysis
  - ν_e CC events will be a background to the NC selected events
    - Consider 2 values of θ_{13}: 0 and the CHOOZ limit

NC Analysis – Far Results

- Far spectrum is consistent with no deficit in the NC rate



- Can measure probability to remain active ν

$$R \equiv \frac{\text{Data - Bkg}}{\text{Signal}}$$

Without ν_e appearance: R = 1.04 $\pm$0.08(stat) $\pm$0.07(sys)

With ν_e appearance: R = 0.94 $\pm$0.08(stat) $\pm$0.07(sys)

- See Backhouse's talk to learn how fits to the spectrum can be interpreted within the context of a physical model

ν_e CC Appearance Analysis

with 3.14 x 10^{20} POT

Limits on θ_{13}

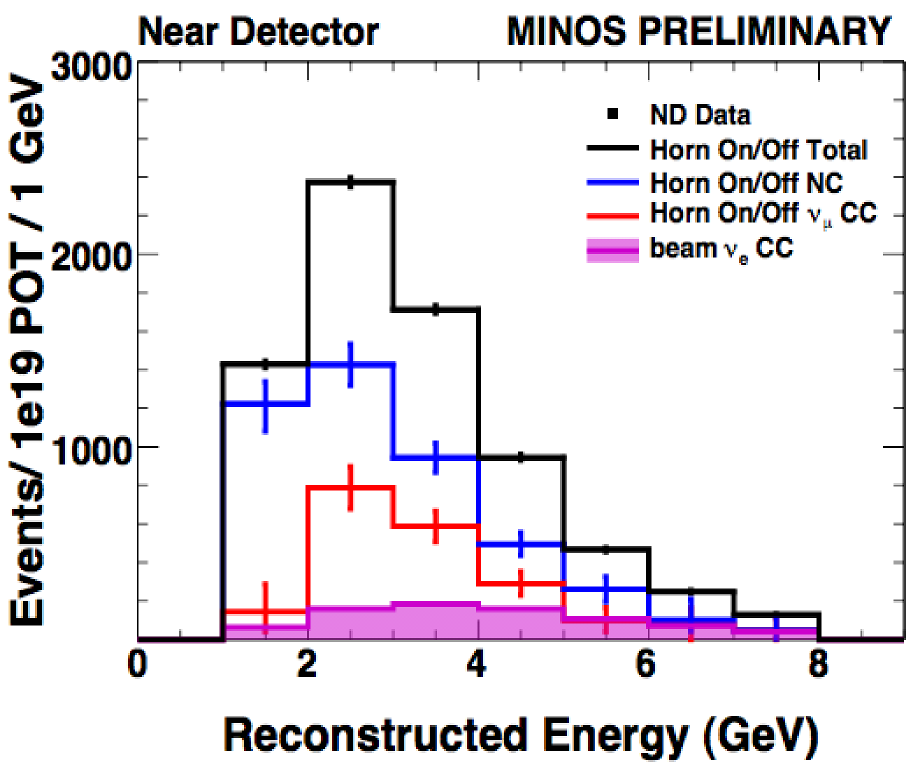
To be submitted to PRL

ν_e CC Appearance – Purpose and Selection

Searching for subdominant $\nu_\mu \rightarrow \nu_e$ oscillations

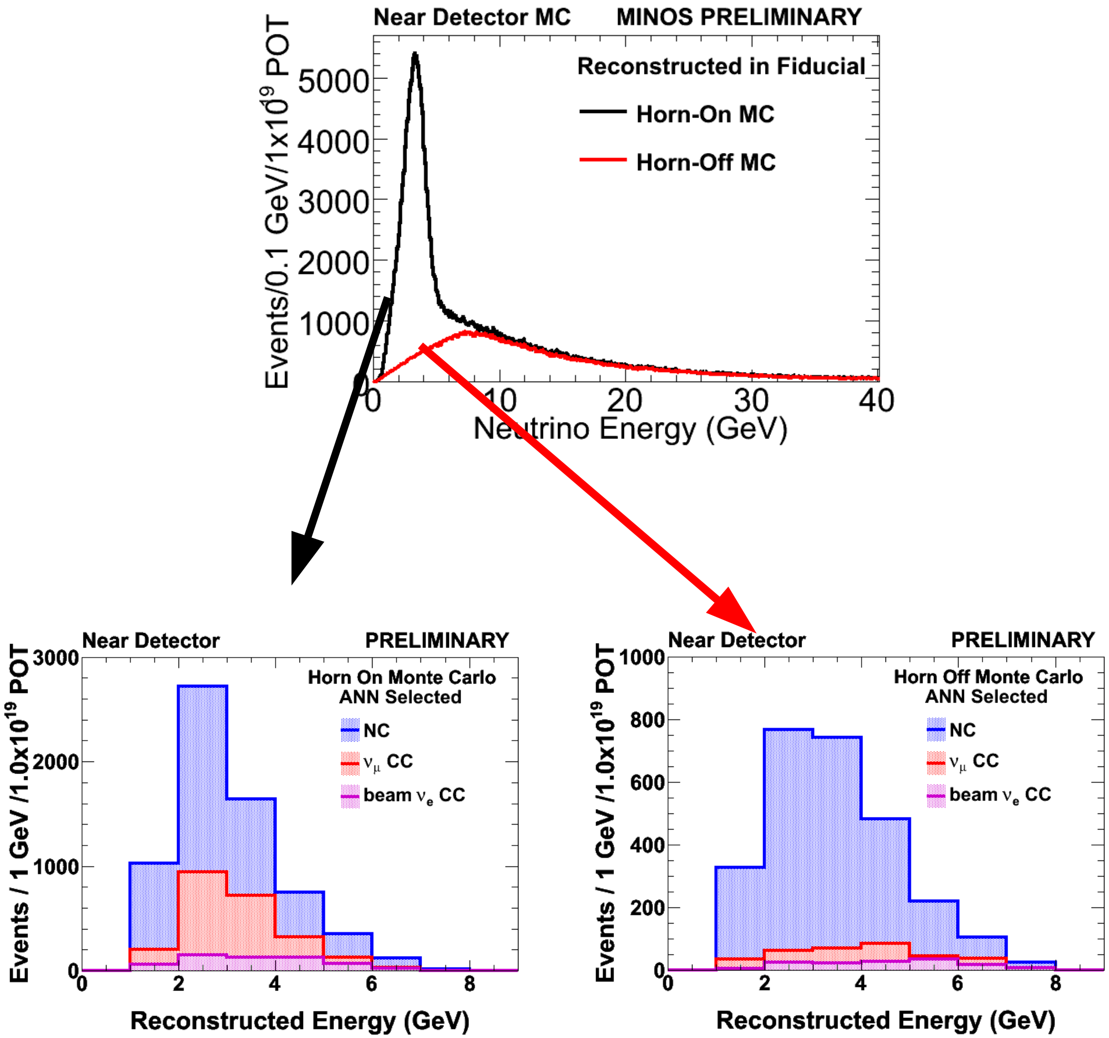
$$P(\nu_\mu \rightarrow \nu_e) \approx \sin^2(\theta_{23})\sin^2(2\theta_{13})\sin^2(1.27\Delta m^2 L/E) + \ldots$$

- Constraining θ_{13} by looking for an excess of ν_e-like events at the Far Detector
- Select electromagnetic shower topologies with neural network
- Background:
  - π^0's generated via NC or deep-inelastic ν_μ-CC interactions
  - τ in FD from oscillations
  - Non-oscillation beam ν_e
- Measure background rate at Near
- Extrapolate to Far by component



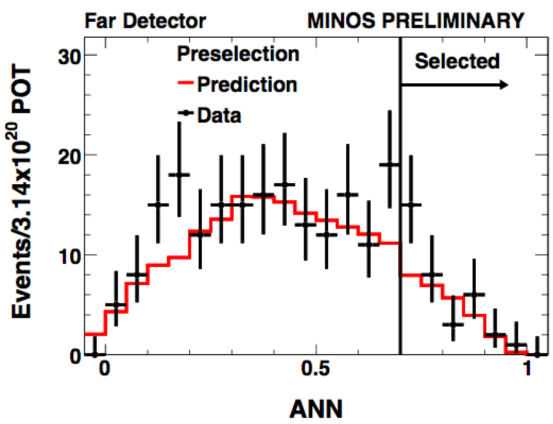
ν_e CC Appearance – Background Composition

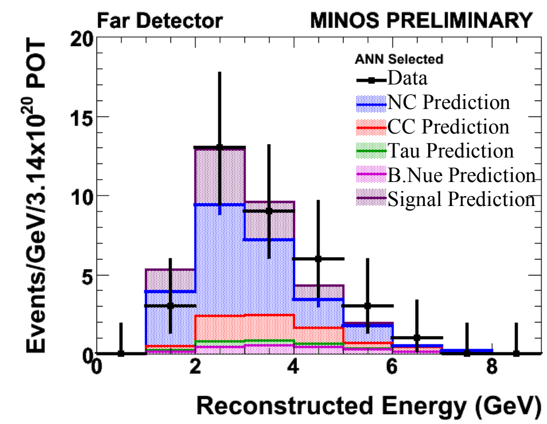
- Note background components extrapolate differently
  - NC interaction unaffected by oscillations
  - CC interactions are affected
- Need to know background components
- Horn-on and Horn-off beam configurations have different NC/CC ratios
- Yields system of linear equations to solve for background components



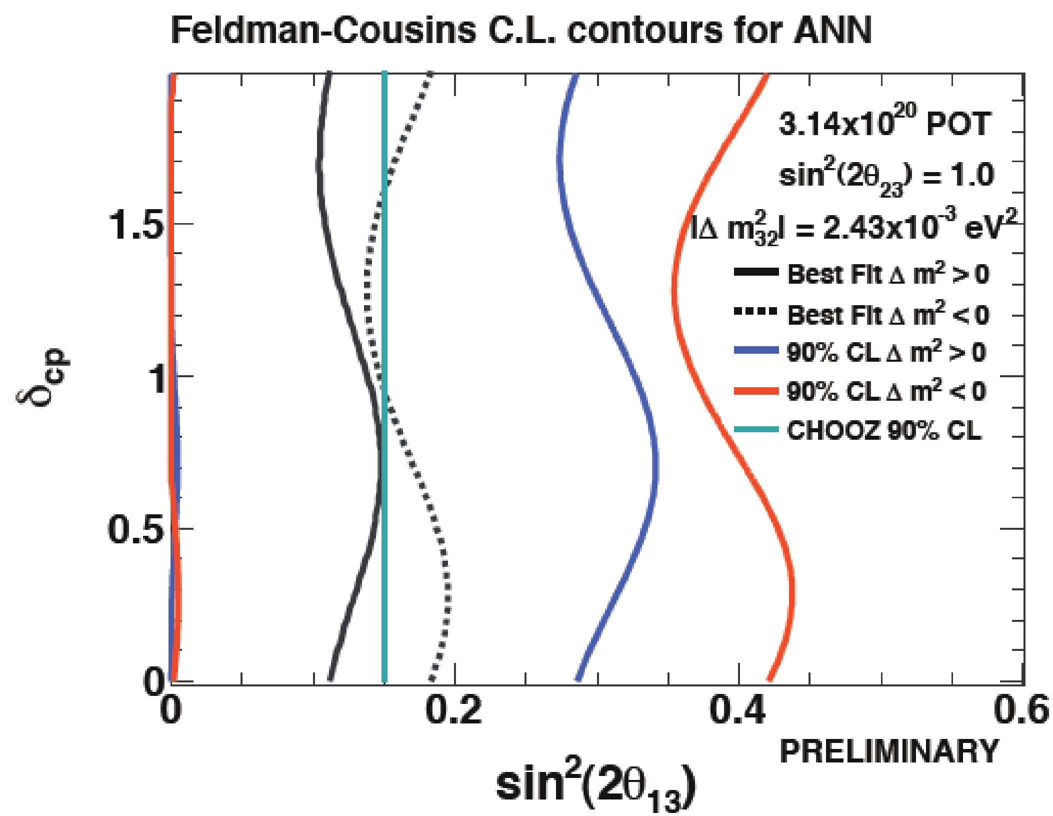
ν_e CC Appearance – Results

- Far Background: 27±5(stat)±2(sys)
- Far Data: 35 events
- 1.5σ excess above background



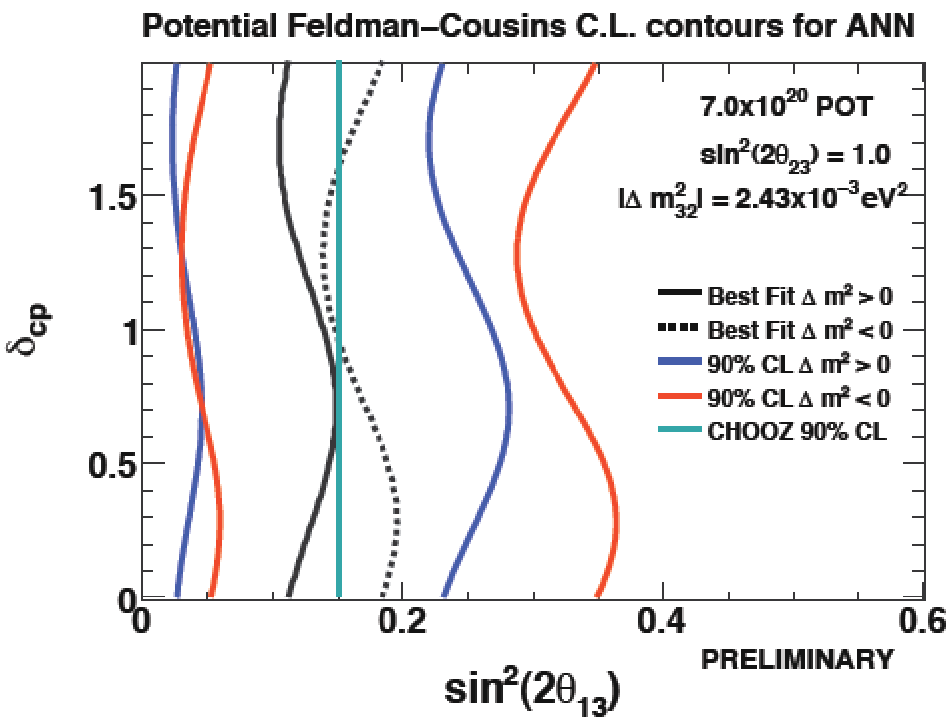


- Set limits based on total number of events using Feldman-Cousins method
- Best Fit and 90% C.L. contours are shown for both hierarchies
  - Assume MINOS best fit values for Δm^2_{32} and $\sin^2(2\theta_{23})$
  - Best fit at CHOOZ limit

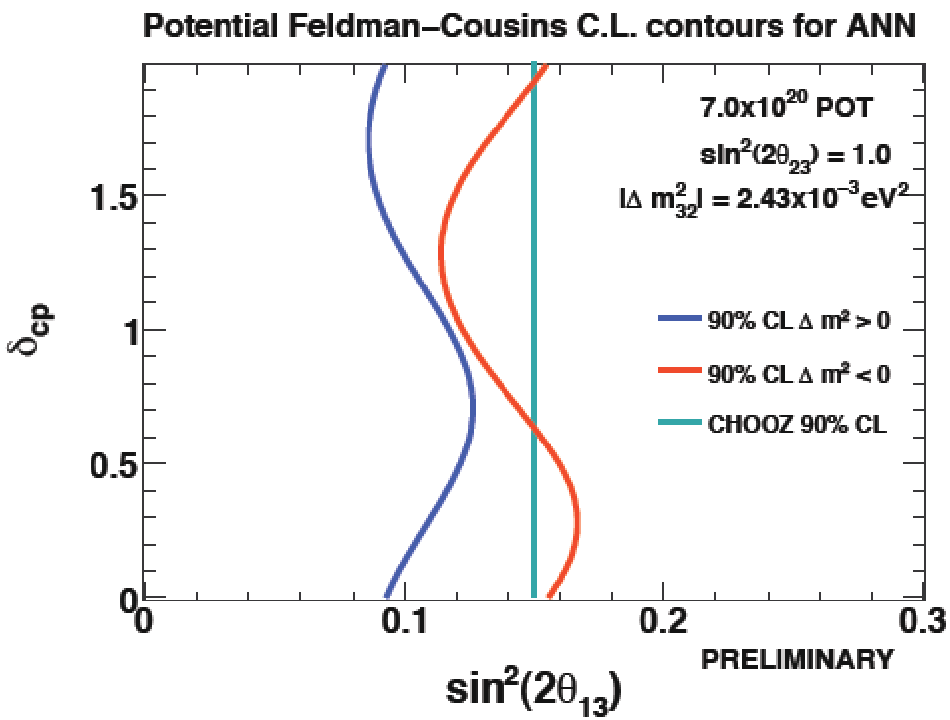


ν_e CC Appearance – Future Prospects

Potential 90% C.L. Contours for 7.0x10^{20} POT



If excess remains with more data



If excess goes away with more data

Blind analysis ongoing

Closing Remarks

- MINOS has analyzed 3×10^{20} POT of beam data
  - More than 7×10^{20} POT has been recorded for ongoing analyses
- Precision ν_μ CC disappearance measurement
  - $|\Delta m^2_{32}| = 2.43\pm0.13\times10^{-3}\,\mathrm{eV}^2$ (68% C.L.)
  - $\sin^2(2\theta_{23})>0.90$ (90% C.L.)
- $\bar{\nu}_\mu$ CC disappearance measurement excludes previously allowed regions of CPT violating phase space
  - Plan to have a dedicated antineutrino run starting this September
- Updated sterile neutrino search
  - See Backhouse's presentation to get the details
- 1.5σ excess in ν_e appearance channel
  - Interesting prospects for the analysis of 7×10^{20} POT of beam data